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Multiplets in the Spectra of O III, O IV, O V and C III

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The spectra of oxygen and carbon have been photographed in the region 100A to 650A with a twenty-one foot grazing incidence vacuum spectrograph. A hot spark was used as the light source. Transitions between $2s^22p3d\,^3D^0$, $^3P^0$, $2s^22p3s\,^3P^0$ and $2s^22p^2\,^3P$ of O III terms were observed. The separation of the levels arising from the lowest electron configuration is thus fixed. Nebular lines fit these term differences very well. In O IV the quartet intercombinations $2s2p^2\,^4P$ to $2s^23s\,^4P^0$, $2s2p3d\,^4D^0$, $^4P^0$ have been found. This connects the two quartet systems and a revised term table is given. The $\Delta\nu$ separations of three O V triplets have been measured but do not agree too well with other data. Two C III triplets, previously observed by Bowen as doublets, have been resolved and fit the calculated $\Delta\lambda$'s.

Introduction

The spectra of ionized oxygen are well known and a list of term values has been collected and published in *Atomic Energy States* by Bacher and Goudsmit. Most of these energy levels have been determined from spectra lines observed above 600A.[1, 2, 3, 4, 5, 6, 7] Some, as in the case of Fowler,[3] have been fixed by observing single lines which in the present analysis have been found to be the multiplets suggested by the previous classification. Examples of such lines are λλλ303A, 305A and 374A. Ericson and Edlén[8] reported a large number of O III, O IV and O V lines in the region 150A to 700A, but did not publish their classification.

Experimental

The oxygen spectra were developed while attempting to excite B by using powdered boron (probably B_7O) with oxygen as an impurity, and H_3BO_3 in copper shell electrodes. The electrodes were used in a "hot spark" light source. The electrical connections were made in the usual way, power being supplied by an 80 kv kenetron bridge set. About 0.05 mf capacity was in the circuit. With this mode of excitation two sparks per sec., each spark having a duration of about 1/30 sec., for a total time of two hours was sufficient to give a well developed spectrum. The oxygen lines were also obtained while using bismuth trioxide in copper shell electrodes to excite the Bi spark spectra.

A twenty-one foot grazing incidence vacuum spectrograph[9] which was constructed by the Mann Instrument Company of Cambridge, Mass., was used to photograph the spectra. The angle of incidence was 87°. The grating was ruled, 30,000 lines per inch, on glass by R. W. Wood and H. M. O'Bryan at Johns Hopkins University.

Results for O III

Table I gives the intensity, wave-length, wave number and classification of the lines observed in the O III multiplets. The term differences ($\Delta\nu$) observed in these multiplets agree very well with those observed by other workers while studying the O III spectrum at longer wave-lengths. The starred wave-lengths in the table were taken from an unpublished list of oxygen standard lines which have been determined by B. Edlén at Upsala in 1931. With the help of the multiplet transitions in Table I it is possible to fix the deepest terms ($2s^22p^2\,^3P_{0,\,1,\,2}$), with respect to the higher terms ($2s^22p3s\,^3P^0$, etc.), more accurately than before. For this reason a revised term table has been included (Table II). This table is

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[1] Mihul, Comptes Rendus **183**, 1035 (1926).

[2] Bowen, Phys. Rev. **29**, 241 (1927).

[3] Fowler, Proc. Roy. Soc. **A117**, 317 (1928).

[4] Freeman, Proc. Roy. Soc. **A124**, 654 (1929).

[5] Freeman, Proc. Roy. Soc. **A127**, 330 (1930).

[6] Bowen and Millikan, Phys. Rev. **26**, 150 (1925).

[7] Edlén, Nature **127**, 744 (1931).

[8] Ericson and Edlén, Zeits. f. Physik **59**, 656 (1929).

[9] Kruger, Rev. Sci. Inst. **4**, 128 (1933).

TABLE I. *New multiplets of O III.*

Int.	λ	ν	Classification
4	374.4344	267,069.5	$2s^22p^2\,{}^3P_2-2s^22p3s\,{}^3P_1^0$
2	374.3319	267,142.6	$2s^22p^2\,{}^3P_1-2s^22p3s\,{}^3P_0^0$
1	374.1658	267,261.0	$2s^22p^2\,{}^3P_1-2s^22p3s\,{}^3P_1^0$
*10	374.0740	267,326.8	$2s^22p^2\,{}^3P_2-2s^22p3s\,{}^3P_2^0$
2	374.0075	267,374.3	$2s^22p^2\,{}^3P_0-2s^22p3s\,{}^3P_1^0$
5	373.8046	267,519.4	$2s^22p^2\,{}^3P_1-2s^22p3s\,{}^3P_2^0$
		(326,929.4)	$2s^22p^2\,{}^3P_2-2s^22p3d\,{}^3D_1^0$
2	305.8293	326,979.8	$2s^22p^2\,{}^3P_2-2s^22p3d\,{}^3D_2^0$
*10	305.7610	327,052.8	$2s^22p^2\,{}^3P_2-2s^22p3d\,{}^3D_3^0$
1	305.6970	327,121.3	$2s^22p^2\,{}^3P_1-2s^22p3d\,{}^3D_1^0$
5	305.6481	327,173.6	$2s^22p^2\,{}^3P_1-2s^22p3d\,{}^3D_2^0$
3	305.5909	327,234.8	$2s^22p^2\,{}^3P_0-2s^22p3d\,{}^3D_1^0$
*7	303.7920	329,172.6	$2s^22p^2\,{}^3P_2-2s^22p3d\,{}^3P_2^0$
1	303.6903	329,283.2	$2s^22p^2\,{}^3P_2-2s^22p3d\,{}^3P_1^0$
1	303.6151	329,353.6	$2s^22p^2\,{}^3P_1-2s^22p3d\,{}^3P_2^0$
1	303.5067	329,482.1	$2s^22p^2\,{}^3P_1-2s^22p3d\,{}^3P_1^0$
1	303.4526	329,540.7	$2s^22p^2\,{}^3P_1-2s^22p3d\,{}^3P_0^0$
1	303.4014	329,596.4	$2s^22p^2\,{}^3P_0-2s^22p3d\,{}^3P_1^0$

the same as that in Bacher and Goudsmit when 60.53 cm^{-1} has been subtracted from all terms above and including the $2s^22p\,3s$ terms in Bacher and Goudsmit. The $2s^22p^2\,{}^1D_2$ and ${}^1S_0$ terms can be fixed equally well by taking the values for the transitions $2s^22p^2\,{}^1D_2-2s^22p3s\,{}^1P_1^0$ and $2s^22p^2\,{}^1S_0-2s^22p3s\,{}^1P_1^0$ from the wave-lengths in Edlén's unpublished list. They are 395.558A (252,807.4 cm^{-1}) and 434.975A (229,898.3 cm^{-1}), respectively. The corrected term value of $2s^22p3s\,{}^1P_1^0$ is 273,087.04 cm^{-1}. This gives $2s^22p^2\,{}^1D_2$ a value 20,279.6 cm^{-1} and ${}^1S_0$ a value 43,188.7 cm^{-1} as given in Table II.

Wright[10] has observed O III nebular lines of

λ(air)	4363.21A ν(vac)	22,912.49 cm^{-1}
	4958.91A	19,967.12 cm^{-1}
	5006.84A	20,160.11 cm^{-1}

Becker and Grotrian[11] have assumed that these nebular lines represent transitions between the $2s^22p^2\,{}^3P_{2,\,1}$, ${}^1D_2$, ${}^1S_0$ terms. By then calculating the predicted wave-length for the center of density of $\lambda\lambda$374.3A and 305.7A,[3] and taking into account the theoretical intensity of the components of all transitions of ${}^3P-{}^3P^0$ and ${}^3P-{}^3D^0$ it is found these calculated values fit the experimental value within the limit of error. It is concluded that the classification is correct.

TABLE II. *Partially revised term table for O III.**

Term	Term value with respect to $2s2p^2\,{}^3P_0=0$
$2s^22p^2\,{}^3P_0$	0
$2s^22p^2\,{}^3P_1$	113.5
$2s^22p^2\,{}^3P_2$	305.4
$2s^22p^2\,{}^1D_2$	20,279.6
$2s^22p^2\,{}^1S_0$	43,188.7
$2s^22p3s\,{}^3P_0^0$	267,255.9
$2s^22p3s\,{}^3P_1^0$	267,374.3
$2s^22p3s\,{}^3P_2^0$	267,632.2
$2s^22p3d\,{}^3D_1^0$	327,234.8
$2s^22p3d\,{}^3D_2^0$	327,287.1
$2s^22p3d\,{}^3D_3^0$	327,360.1
$2s^22p3d\,{}^3P_2^0$	329,476.9
$2s^22p3d\,{}^3P_1^0$	329,596.4
$2s^22p3d\,{}^3P_0^0$	329,655.0

* Terms arising from the $2s2p^3$ configuration are correct as given in *Atomic Energy States*, Bacher and Goudsmit with respect to the term values in this table. All terms above and including the $2s^22p3s$ terms have a value too high by 60.53 cm^{-1} with respect to the values in the above table.

Since all of the components of the transitions $2s^22p^2\,{}^3P_{2,\,1,\,0}-2s^22p3s\,{}^3P^0{}_{2,\,1,\,0}$ and $2s^22p^2\,{}^3P_{2,\,1,\,0}-2s^22p3d\;\;{}^3D^0{}_{3,\,2,\,1}\;\;{}^3P^0{}_{2,\,1,\,0}$ have been found during the present study, it is no longer necessary to assume that the nebular lines are the above suggested transitions. A direct check can be made from the term table. This follows from Table III.

TABLE III. *Comparison of term differences in $2s^22p^2\,{}^3P_{2,\,1}$ ${}^1D_2$, ${}^1S_0$ terms and nebular lines.*

Term difference in cm^{-1}	ν cm^{-1} of nebular lines
${}^1S_0-{}^1D_2=22{,}909.1$	22,912.49
${}^1D_2-{}^3P_2=19{,}974.2$	19,967.12
${}^1D_2-{}^3P_1=20{,}166.1$	20,160.11

RESULTS OF O IV

Table IV gives the wave-lengths of lines resulting from $2s2p^2$, ${}^4P-2s2p3s\,{}^4P^0$ and $2s2p3d\,{}^4D^0$, ${}^4P^0$ transitions. This enables the two quartet systems (listed separately in Bacher and Goudsmit) to be connected. A revised quartet term table is given in Table V. Freeman[5] observed the doublets 279.935A, 279.632A and 238.575A, 238.362A as single lines and gave them the correct classification. Edlén[8] has also observed the 238A doublet. The starred wave-lengths were taken from Edlén's unpublished list of oxygen standards.

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[10] Wright, Publ. of the Lick Obs. **13**, Part VI (1918).

[11] Ergebnisse der Exakten Naturwissenschaften **7**,61–4.

TABLE IV. *New multiplets of O IV.*

Int.	λ obs.	ν obs.	calc. ν	Classification
20	279.935	357,225.8		$2s^22p\ ^2P_{3/2} - 2s^23s\ ^2S_{1/2}$
10	279.632	357,612.8		$2s^22p\ ^2P_{1/2} - 2s^23s\ ^2S_{1/2}$
3	272.3181	367,217.5	367,221.6	$2s2p^2\ ^4P_{5/2} - 2s2p3s\ ^4P_{3/2}{}^0$
3	272.2808	367,267.9	367,265.5	$2s2p^2\ ^4P_{3/2} - 2s2p3s\ ^4P_{1/2}{}^0$
1	272.1859	367,396.0	367,400.6	$2s2p^2\ ^4P_{3/2,\ 1/2} - 2s2p3s\ ^4P^0{}_{3/2,\ 1/2}$
10	272.1327	367,467.8	367,466.5	$2s2p^2\ ^4P_{5/2} - 2s2p3s\ ^4P_{5/2}{}^0$
4	272.0818	367,536.5	367,535.6	$2s2p^2\ ^4P_{1/2} - 2s2p3s\ ^4P_{3/2}{}^0$
5	271.9964	367,651.9	367,647.5	$2s2p^2\ ^4P_{3/2} - 2s2p3s\ ^4P_{5/2}{}^0$
*20	238.575	419,155.4		$2s^22p\ ^2P_{3/2} - 2s^23d\ ^2D_{5/2,\ 3/2}$
10	238.362	419,530.0		$2s^22p\ ^2P_{1/2} - 2s^23d\ ^2D_{1/2}$
			(428,031.3)	$2s2p^2\ ^4P_{5/2} - 2s2p3d\ ^4D_{3/2}{}^0$
1	233.6022	428,078.1	428,078.0	$2s2p^2\ ^4P_{5/2} - 2s2p3d\ ^4D_{5/2}{}^0$
*8	233.5660	428,144.5	428,142.6	$2s2p^2\ ^4P_{5/2} - 2s2p3d\ ^4D_{7/2}{}^0$
			(428,183.4)	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4D_{1/2}{}^0$
1	233.5272	428,216.0	428,212.3	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4D_{3/2}{}^0$
4	233.5016	428,262.8	428,259.0	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4D_{5/2}{}^0$
1.5	233.4669	428,326.3	428,318.4	$2s2p^2\ ^4P_{1/2} - 2s2p3d\ ^4D_{1/2}{}^0$
1	233.4548	428,348.3	428,347.3	$2s2p^2\ ^4P_{1/2} - 2s2p3d\ ^4D_{3/2}{}^0$
*10	231.3020	432,335.2	432,330.5	$2s2p^2\ ^4P_{5/2} - 2s2p3d\ ^4P_{5/2}{}^0$
3	231.2433	432,445.0	432,443.9	$2s2p^2\ ^4P_{5/2} - 2s2p3d\ ^4P_{3/2}{}^0$
4	231.2053	432,516.0	432,511.5	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4P_{5/2}{}^0$
1	231.1475	432,624.2	432,624.9	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4P_{3/2}{}^0$
2	231.1087	432,696.8	432,704.1	$2s2p^2\ ^4P_{3/2} - 2s2p3d\ ^4P_{1/2}{}^0$
4	231.0777	432,757.9	432,759.9	$2s2p^2\ ^4P_{1/2} - 2s2p3d\ ^4P_{3/2}{}^0$
1	231.0333	432,838.0	432,839.1	$2s2p^2\ ^4P_{1/2} - 2s2p3d\ ^4P_{1/2}{}^0$

TABLE V. *Revised term table for O IV quartets.*

Term	Term value with respect to $2s2p^2\ ^4P=0$	Term	Term value with respect to $2s2p^2\ ^4P=0$
$2s2p^2\ ^4P_{1/2}$	0	$2s2p3d\ ^4F_{3/2}{}^0$	423,719.5
$2s2p^2\ ^4P_{3/2}$	135	$2s2p3d\ ^4F_{5/2}{}^0$	423,798.3
$2s2p^2\ ^4P_{5/2}$	316	$2s2p3d\ ^4F_{7/2}{}^0$	423,910.7
$2p^3\ ^4S_{3/2}{}^0$	160,100	$2s2p3d\ ^4F_{9/2}{}^0$	424,064.8
$2s2p3s\ ^4P_{1/2}{}^0$	367,400.5	$2s2p3d\ ^4D_{1/2}{}^0$	428,318.4
$2s2p3s\ ^4P_{3/2}{}^0$	367,535.6	$2s2p3d\ ^4D_{3/2}{}^0$	428,347.3
$2s2p3s\ ^4P_{5/2}{}^0$	367,782.5	$2s2p3d\ ^4D_{5/2}{}^0$	428,394.0
$2s2p3p\ ^4D_{1/2}$	386,887.4	$2s2p3d\ ^4D_{7/2}{}^0$	428,458.6
$2s2p3p\ ^4D_{3/2}$	386,966.2	$2s2p3d\ ^4P_{5/2}{}^0$	432,646.5
$2s2p3p\ ^4D_{5/2}$	387,101.7	$2s2p3d\ ^4P_{3/2}{}^0$	432,759.9
$2s2p3p\ ^4D_{7/2}$	387,311.4	$2s2p3d\ ^4P_{1/2}{}^0$	432,839.1
$2s2p3p\ ^4S_{3/2}$	403,029.8		
$2s2p3p\ ^4P_{1/2}$	407,399.7		
$2s2p3p\ ^4P_{3/2}$	407,494.2		
$2s2p3p\ ^4P_{5/2}$	407,623.3		

TABLE VI. *Triplets of O V.*

Int.	λ obs.	ν obs.	Δν	Classification
*10	215.2000	464,684.0	305.8	$2s2p\ {}^3P_2-2s3s\ {}^3S_1$
5	215.0585	464,989.8	125.0	$2s2p\ {}^3P_1-2s3s\ {}^3S_1$
2	215.0007	464,114.8		$2s2p\ {}^3P_0-2s3s\ {}^3S_1$
*50	192.9100	518,376.4	291.2	$2s2p\ {}^3P_2-2s3d\ {}^3D_{3,2,1}$
25	192.8017	518,667.6	134.6	$2s2p\ {}^3P_1-2s3d\ {}^3D_{3,2,1}$
10	192.7517	518,802.2		$2s2p\ {}^3P_0-2s3d\ {}^3D_{3,2,1}$
8	151.5689	659,766.0	300.0	$2s2p\ {}^3P_2-2s4d\ {}^3D_{3,2,1}$
*2	151.5000	660,066.0	126.3	$2s2p\ {}^3P_1-2s4d\ {}^3D_{3,2,1}$
0	151.471	660,192.3		$2s2p\ {}^3P_0-2s4d\ {}^3D_{3,2,1}$

Table VI lists three triplets of O V and their Δν separations. These are different from those previously reported.[6, 7] The $2s2p\ {}^3P_2-{}^3P_1$ term separation is probably 306 cm^{-1} but ${}^3P_1-{}^3P_0$ is more nearly 125 cm^{-1} than the previously reported value 135 cm^{-1}. The lines at 192.9A representing the $2s2p\ {}^3P_{2,1,0}-2s3d\ {}^3D_{3,2,1}$ transition do not have the above separations but this is probably because of the small splitting of the ${}^3D$ terms which are unresolved. In the 150A triplet the separations are again essentially those of the $2s2p\ {}^3P_{2,1,0}$ states.

Two C III triplets which were previously observed as doublets by Bowen[12] have been resolved and are listed in Table VII. The observed Δλ's check the calculated Δλ's so that Bowen's classification is substantiated.

TABLE VII. *Triplets of C III.*

Int.	calc λ's	calc Δλ's	obs Δλ's	Classification
6	535.430	0.161	0.167	$2s2p\ {}^3P_2{}^0-2s3s\ {}^3S_1$
3	535.269	0.068	0.065	$2s2p\ {}^3P_1{}^0-2s3s\ {}^3S_1$
1	535.201			$2s2p\ {}^3P_0{}^0-2s3s\ {}^3S_1$
10	459.634	0.118	0.113	$2s2p\ {}^3P_2{}^0-2s3d\ {}^3D_{3,2,1}$
6	459.516	0.050	0.053	$2s2p\ {}^3P_1{}^0-2s3d\ {}^3D_{2,1}$
3	459.466			$2s2p\ {}^3P_0{}^0-2s3d\ {}^3D_1$

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[12] Bowen, Phys. Rev. **38**, 128 (1931).